



Design of a Modular 5-kW Power Processing Unit for the Next-Generation 40-cm Ion Engine

Luis R. Piñero
Glenn Research Center, Cleveland, Ohio

Thomas Bond, Don Okada, Janusz Pyter, and Steve Wiseman
Boeing Electron Dynamic Devices, Torrance, California

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Luis R. Piñero
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Thomas Bond, Don Okada, Keith Phelps, Janusz Pyter, and Steve Wiseman
Boeing Electron Dynamic Devices
Torrance, California 90509

NASA Glenn Research Center is developing a 5/10-kW ion engine for a broad range of mission applications. Simultaneously, a 5-kW breadboard power processing unit is being designed and fabricated. The design includes a beam supply consisting of four 1.1 kW power modules connected in parallel, equally sharing the output current. A novel phase-shifted/pulse-width-modulated dual full-bridge topology was chosen for its soft-switching characteristics. The proposed modular approach allows scalability to higher powers as well as the possibility of implementing an N+1 redundant beam supply. Efficiencies in excess of 96 percent were measured during testing of a breadboard beam power module. A specific mass of 3.0 kg/kW is expected for a flight PPU. This represents a 50 percent reduction from the state of the art NSTAR power processor.

Introduction

A 5/10 kW-class ion propulsion system (IPS) is being considered for various NASA missions including Earth-orbit and deep-space missions like Europa Lander, Saturn Ring Observer, Neptune Orbiter, Comet Nucleus Sample Return, and Venus Surface Sample Return.^{1,2} NASA Glenn Research Center (NASA-GRC) is pursuing the development of this system under its On-Board Propulsion Program. The design goals include a 1 to 10 kW power throttling range, 550 kg of xenon throughput capability, 12 kg thruster mass, and 1/2-NSTAR recurring cost. The purpose of this effort is to advance ion engine technology beyond state of the art NSTAR technology.

A 40-cm ion engine is in the design phase using the successful 'derating' approach of the NSTAR ion engine. It is expected to have performance ranging between 2500 to 3900 seconds specific impulse, 49 to 360 mN of thrust, and 56 to 72 percent efficiency for the 1 to 10 kW power range.³

Simultaneously, a 5-kW breadboard power processing unit (PPU) is being designed and built by Boeing Electron Dynamics Devices (BEDD) under contract with NASA-GRC. The PPU is being designed to yield a total efficiency in excess of 92 percent and a total flight-packaged mass of less than 15 kg. This represents a specific mass of 3.0 kg/kW which is half that of the NSTAR PPU.

The 5-kW PPU effort consists of three phases. Phase I includes the overall conceptual design of the PPU and fabrication of the breadboard beam supply. The results of this effort are reported herein. Phase II consists of fabrication of a complete breadboard PPU including integration with a laboratory model 40-cm ion engine. Phase III involves design and fabrication of an engineering model PPU and integration with an engineering model thruster.

The beam supply design is critical to obtain high efficiency and low mass since up to 91 percent of the power is processed by this high-voltage unit. A modular approach consisting of four 1.1 kW modules operating in parallel to supply power to the thruster was chosen for this design. Further increases in power or N+1 redundancy could be implemented by paralleling additional modules. A dual bridge phase modulated topology was used in this design with the intent of implementing a design that operates with low switching losses.

This paper describes the breadboard beam supply and overall PPU implementation. Also, included is preliminary efficiency data from bench-top testing on the breadboard beam supply.

System Overview

The envisioned 5-kW IPS is based on the highly successful NSTAR propulsion system used on the Deep Space 1 spacecraft.^{4,5,6} The system would consist of a 40 cm xenon ion engine, PPU, Xenon Feed System (XFS), and Digital Control and Interface Unit (DCIU). Figure 1 shows a simplified block diagram of this system. Laboratory model 40-cm ion engines for a possible 5-kW IPS are currently being developed and tested at NASA-GRC based on the NSTAR design philosophy. The NSTAR DCIU provided MIL-STD-1553 communications between the IPS and the spacecraft, RS-422 communications between multiple PPUs, and valve drivers for the XFS. This DCIU could be used for a future mission with appropriate firmware and/or hardware modifications. The NSTAR XFS could also be used in a future mission. However, recent developments in proportional valves could result

in a significantly simpler, smaller, and lighter XFS.⁷ Details on the PPU and the beam supply are discussed below.

PPU Specifications

Figure 2 illustrates a typical ion PPU including up to six power supplies and electronics for additional functions.^{8, 9} The beam and the accelerator supplies provide high voltages to accelerate the ions. The discharge supply provides current to the discharge cathode to ionize the xenon propellant. The neutralizer keeper supply provides current to the neutralizer cathode to ionize and provide a "plasma bridge" for electrons to neutralize the ion beam. The heater supplies raise the temperature of the cathodes to emission temperature during ignition. Finally, the housekeeping supply provides power to recycle, gate drive, control, and telemetry circuits.

Significant reductions in mass and complexity can be obtained by using multiple output or multiple function power supplies. A multiple output supply uses various secondary windings connected to a common primary power stage. A multiple function supply uses the one power supply to power various thruster inputs. Several of these techniques have been successfully demonstrated in the past.^{6,8-10}

Critical electrical and mechanical specifications for the PPU are listed in Table 1. The PPU uses a high voltage bus operating from 80 to 160 V to provide power for the main power conversion electronics and a low voltage bus operating at 22 to 34 V for housekeeping purposes. The beam and accelerator supplies have a regulated voltage output and the others have a regulated current output. Input/output regulation and output ripple of 5 percent or better is also required. The discharge and neutralizer supplies must include a high voltage pulsed ignitor to assist ignition when the hollow cathodes do not breakdown upon application of the power supply open circuit voltage. All the power supplies must be capable of operating under short circuit conditions. Also, the PPU must be capable of operating in a temperature range of -15 to 50 °C, passing

MIL-STD-461 for electromagnetic interference (EMI), and exchanging parts with radiation-hardened equivalents. Power conversion efficiency for the PPU should be better than 92 percent and the total mass must be less than 15 kg.

Beam Power Supply Design

Beam supply design is critical since it processes 80 to 91 percent of the total power into a 5-kW IPS. The three major losses in a typical power supply are conduction, switching, and core losses. The majority of conduction losses are caused by currents flowing through magnetic windings, the on-resistance of the MOSFETs, and the output rectifiers. Switching losses are generated in the MOSFETs during the turn-on/turn-off transitions and in the output rectifiers during reverse recovery. Core losses occur in the magnetic cores due to the excitation of the material. To yield high efficiency design, all these losses must be minimized for the complete input and output range.

Generally, magnetic components are the heaviest electronic components in a power supply. Their size and mass can be reduced by increasing the switching frequency. However, this will increase the switching losses so a careful trade-off study must be done to choose the optimum switching frequency for the design. Using ferrite cores can also help reduce PPU mass since they are lightweight and have low core losses when compared to metal cores. A highly efficient design will further help to decrease PPU mass by reducing base-plate and component thermal bracket requirements. In addition, a simple circuit design not only increases reliability but also reduces printed circuit board (PCB) area which could translate into lower PPU mass. Finally, a simpler design reduces the amount of housekeeping power which reduces the size of the housekeeping supply.

The approach selected for the beam supply is a phase-shift/pulse-width modulated dual-bridge converter. This topology consists of two full-bridge power stages operating in parallel on the primary side. The secondary operates in either

parallel or series through a six-diode rectifier arrangement. The output low-pass filter consists of an inductor and a capacitor. A simplified diagram of this circuit is shown in Figure 3. A switching frequency of 50 kHz for each full bridge portion of the circuitry was implemented. The resulting switching frequency at the output of the converter is 100 kHz. Operation at higher switching frequency than the existing NSTAR power processor was done with the intent to reduce the size of the magnetic components. While the breadboard was not implemented with the optimum size magnetics, demonstration of feasibility of the approach was achieved.

The converter operates in phase-shift mode for high output voltage operation. During this mode of operation, all MOSFETs operate at 50 percent duty cycle. Regulation is obtained by the amount of phase-shift between the A-C or B-D MOSFET pairs. When they are in phase, the transformer secondaries operate in series applying twice the transformer voltage onto the output filter. When they are out of phase, the secondaries operate in parallel applying only the transformer voltage to the output filter. As the converter is required to provide a higher output voltage, the phase-shift control circuitry commands the bridges to operate increasingly in-phase. This results in a higher average voltage at the output filter. During phase-shift mode operation, load currents tend to be equally shared between both bridges on the primary side of the converter. This helps to increase power conversion efficiency by reducing conduction losses. The gate drive timing for the phase-shifted case is shown in Figure 4.

To provide additional regulation range and allow low output voltage operation of the beam supply, the converter also operates in traditional pulse-width-modulation (PWM) mode. When the converter is required to provide lower output voltage the phase shift control circuitry causes the bridges to be operated such that they become increasingly out-of-phase. This results in a lower average voltage at the output filter. This continues until a maximum degree of phase shift of 180 degrees is reached. When this point of operation is reached, the phase shift control circuitry cannot lower the output voltage any further. Then, the converter operates in pulse-

width modulation on each bridge. In this mode of operation, the output voltage is proportional to the gate drive pulse width. A higher output voltage is obtained by increasing the on time of the bridges until 50 percent duty cycle is reached. Past this point, phase-shift operation is resumed to obtain higher output voltages. Gate drives for the PWM mode of operation are shown in Figure 5.

One reason for choosing this topology is that phase-shift modulation allows this design to operate in zero-voltage-switching (ZVS) or zero-current-switching (ZCS) to reduce overall switching losses and obtain higher power conversion efficiency. While the converter operates in phase-shifted mode each bridge switches differently during the switching cycle. The two bridges in this converter are called the leading leg and trailing leg bridges. The operation of the trailing leg bridge is characterized by immediately increasing the voltage at the output filter when it switches to a new state. This bridge can be operated in a zero current switching mode by proper choice of circuit parameters which will decrease the current to very low levels before the bridge switches to a new state. Voltage and current waveforms of this kind of operation are shown in Figure 6, at a 1.0 kW output power level. The leading leg bridge operates so that the voltage at the output filter decreases when this bridge switches to a new state. This bridge can be operated in zero voltage switching also by proper selection of circuit parameters which will reduce the voltage in the MOSFETs before they switch to a new state. Figure 7 shows the waveforms for this case.

Another reason for choosing this topology is that the operation of the converter minimizes the applied voltage on the output filter inductor during operation. During the phase-shift mode of operation, the voltage at the output inductor never decreases to less than the transformer voltage. During the pulse-width mode of operation the voltage never increases above the transformer voltage. This minimizes the size and mass of the output inductor.

This 1.1 kW power module is the building block for a higher power beam supply. Multiple individual power modules can be connected in

parallel at the input as well as the output to obtain a beam power supply capable of operating at higher power. The block diagram shown in Figure 8 shows the basic connection of the individual beam supply modules for a 5-kW PPU. Operation of a current share bus ensures that all modules will operate at the same power level. Another option is implementing N+1 redundancy by paralleling additional modules.

Test Procedure

A beam supply power module was tested for efficiency through its input and output voltage range on a resistive load. Input and output voltage and current were measured using digital multimeters (DMM) and efficiency was calculated as the ratio of output to input power. Housekeeping power is provided on a separate input and not included on these calculations. Efficiency measurements were done at 1500 and 800 V which are maximum and minimum output voltages. For the 1500 V output, the module was operating in phase-shift mode and PWM mode and for the 800 V output, it was operating in PWM mode.

Results and Discussion

Figure 9 shows a plot of efficiency versus input voltage for output power levels of approximately 1.0 kW and 0.3 kW. The efficiency range of the beam supply power module for input voltages between 80 to 160 V at an output power of 1.0 kW and a maximum output voltage of 1500 V is 95.9 to 96.9 percent. The observed variation in efficiency while the input voltage is increased is due to the converter transitioning from phase-shift to pulse-width mode operation. Two of these modules operating in parallel at this power level have comparable maximum output power capability to the NSTAR PPU. At an output power of approximately 0.3 kW and a minimum output voltage of 800 V, the efficiency ranged between 91.6 to 95.9 percent for input voltages between 80 to 160.

Total PPU efficiency projections were done using the measured beam supply efficiency numbers and

estimated efficiencies for the discharge, neutralizer keeper, and accelerator supplies based on the NSTAR PPU performance measurements. The results are shown in Figure 10. The total efficiency for a 5-kW PPU is expected to range from 93 to 95 percent for an output power range from 1 to 5 kW at a nominal input voltage of 100 V. This represents up to 4 percent improvement over the state of the art NSTAR technology.

Conclusions

A 1.1 kW beam supply module for a 5-kW PPU was designed and fabricated. A phase-shift/pulse-width modulated dual-bridge topology operating at a switching frequency of 50 kHz was selected for this design. Efficiencies ranging between 91.6 to 96.9 percent were measured for an input voltage range of 80 to 160 V, an output voltage range of 800 to 1500 V, and output powers from 0.3 to 1.0 kW. This beam supply could result in a PPU with a total efficiency between 93 and 95 percent at a nominal input voltage of 100 V. This is up to 4 percent improvement over the NSTAR PPU. High efficiency is obtained by low switching losses from the phase-shifted, ZVS/ZCS operation and low conduction losses. Obtaining this kind of efficiency while being able to maintain the mass of the overall PPU to a level approaching 15 kg will make a 5-kW ion propulsion very attractive for many planetary missions.

Future work will include designing and fabricating breadboard discharge, neutralizer keeper, accelerator, and heater supplies and integrating them with the beam supply into a complete breadboard PPU. Then, the breadboard PPU will be integrated with a laboratory model 40-cm ion engine.

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Table 1. PPU Specifications

	BREADBOARD	BRASSBOARD
Input Voltage	80 - 160 V _{DC} and 24 - 34 V _{DC}	80 - 160 V _{DC} and 24 - 34 V _{DC}
Efficiency	> 0.92	> 0.92
Mass	NA	< 15 kg
Interface	Analog	Analog
Operating Temp	NA	-15 to 50 °C
EMC/EMI	NA	MIL-STD-461C
Radiation	Parts with radiation hardened equivalents	Parts with radiation hardened equivalents

Table 2. PPU Outputs Specifications

	BEAM	ACCEL	DISCHARGE	NEUTRALIZER	HEATERS
Output Voltage	800 - 1500 V _{DC}	-(350 - 150) V _{DC}	15.0 - 35.0 V _{DC}	8.0 - 32.0 V _{DC}	3.0 - 12.0 V _{DC}
Output Current	0.3 - 3.0 A _D	0.0005-0.03 A _{DC} 0.5 A surge for 100 ms	3.0 - 25.0 A _{DC}	1.0 to 2.0 A _{DC}	3.5 to 8.5 A _{DC}
Ignitor Pulse			650 V _{peak} 10 μs rise time 10 Hz rep. Rate 150 V/μs	650 V _{peak} 10 μs rise time 10 Hz rep rate 150 V/μs	
Reg. Mode	Constant Voltage	Constant Voltage	Constant Current	Constant Current	Constant Current
Line/Load Reg.	5 %	5 %	5 %	5 %	5 %
Output Ripple	5 %	5 %	5 %	5 %	5 %

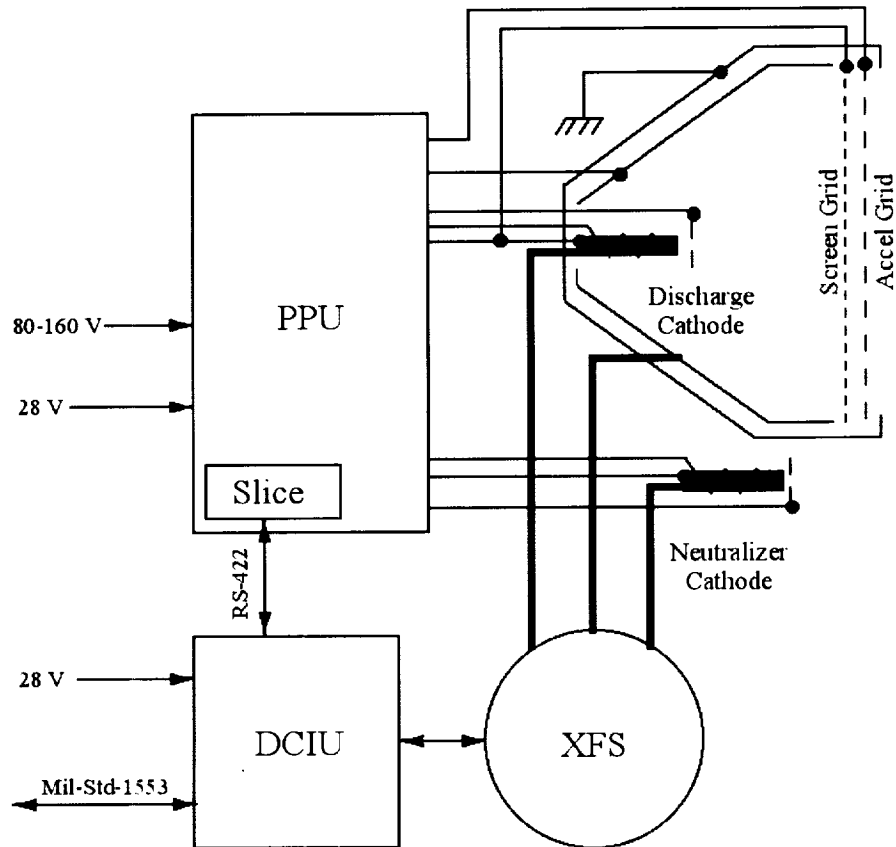


Figure 1. Simplified Ion Propulsion System Block Diagram

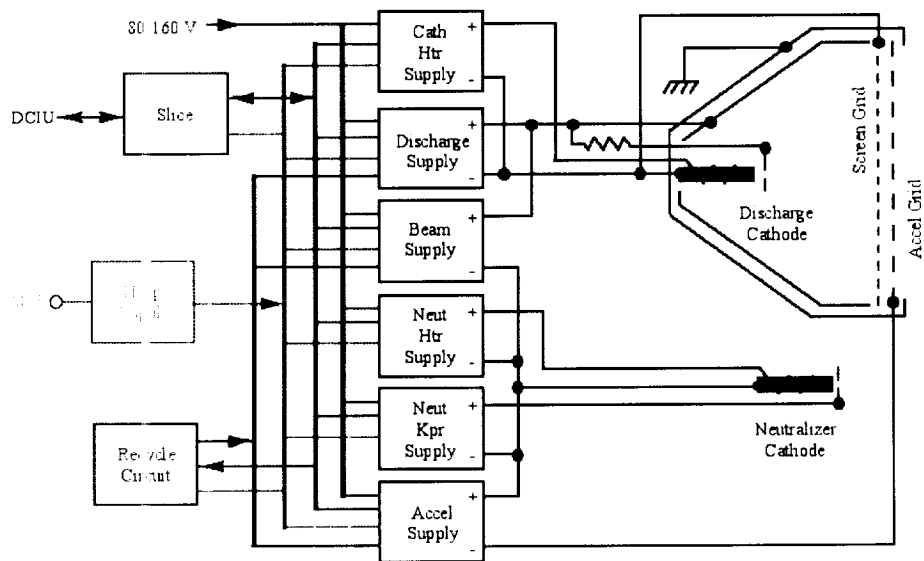


Figure 2. Simplified Power Processing Unit Block Diagram

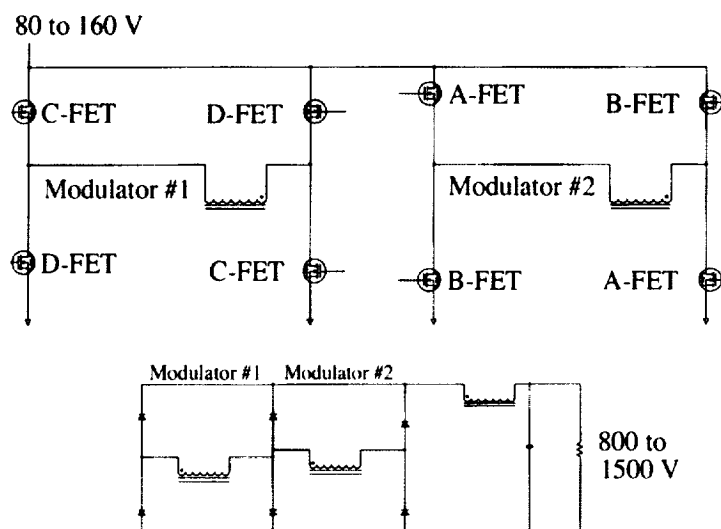


Figure 3. Phase-Shifted / Pulse-Width Modulated Dual-Bridge Topology and Basic Operation Waveforms

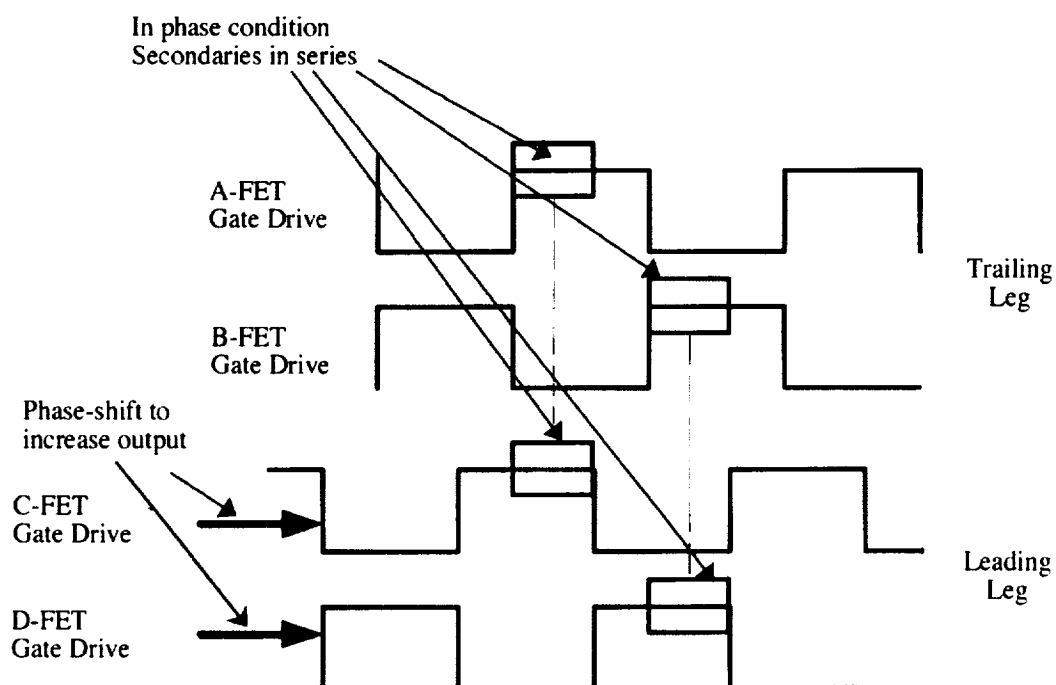


Figure 4. Phase-Shift Modulation Gate Drives

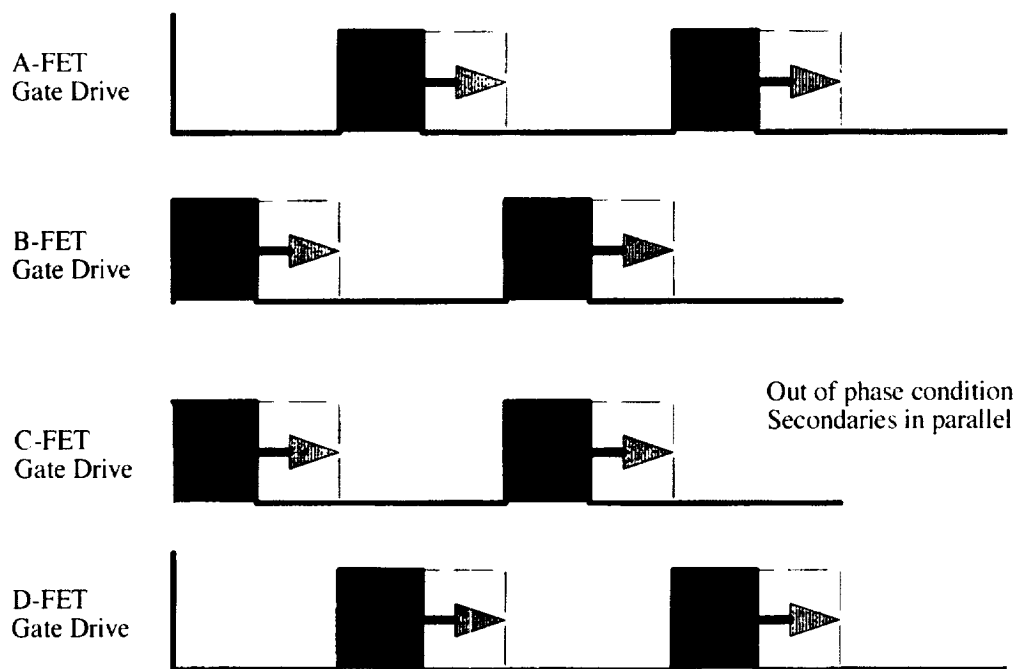


Figure 5. Pulse-Width Modulation Gate Drives

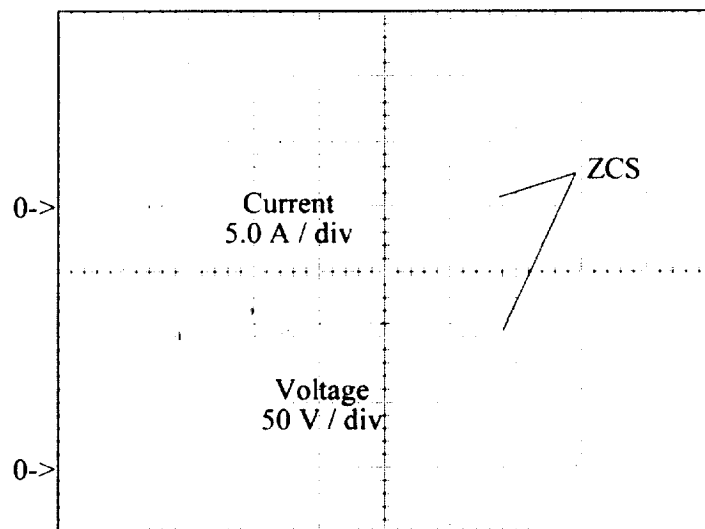


Figure 6. Zero-Current-Switching Waveforms

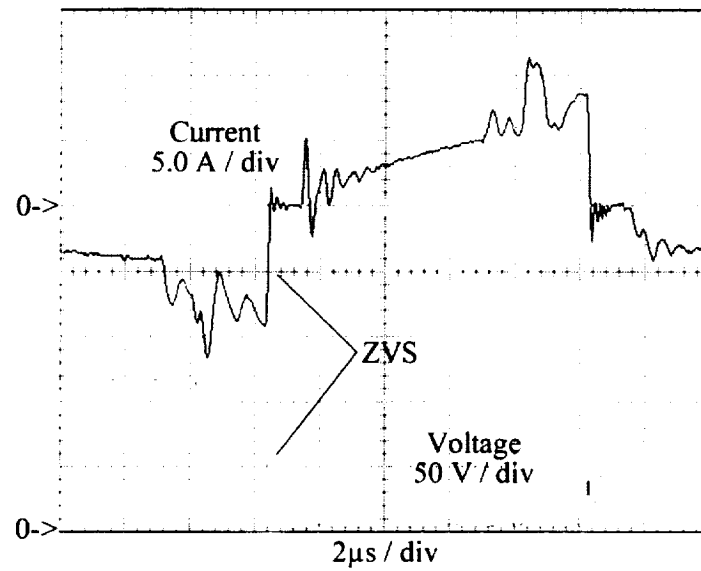


Figure 7. Zero-Voltage-Switching Waveforms

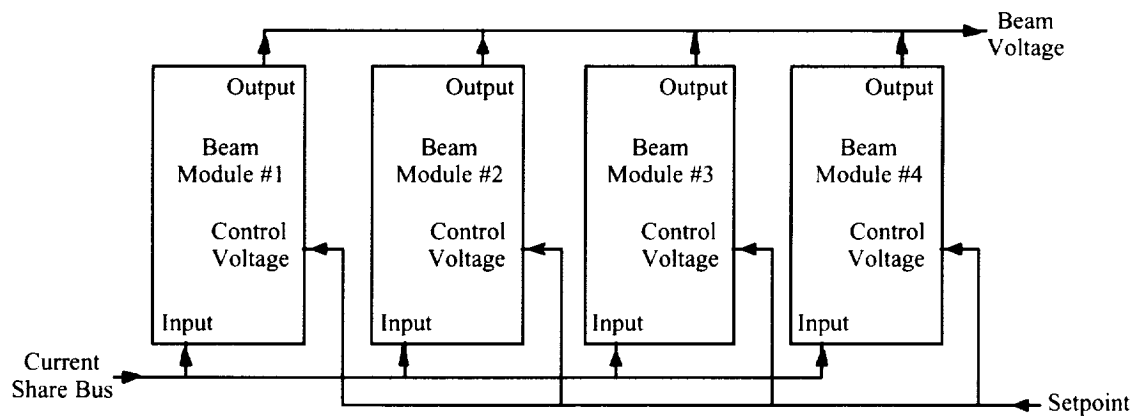


Figure 8. 5 kW Modular Beam Supply Block Diagram

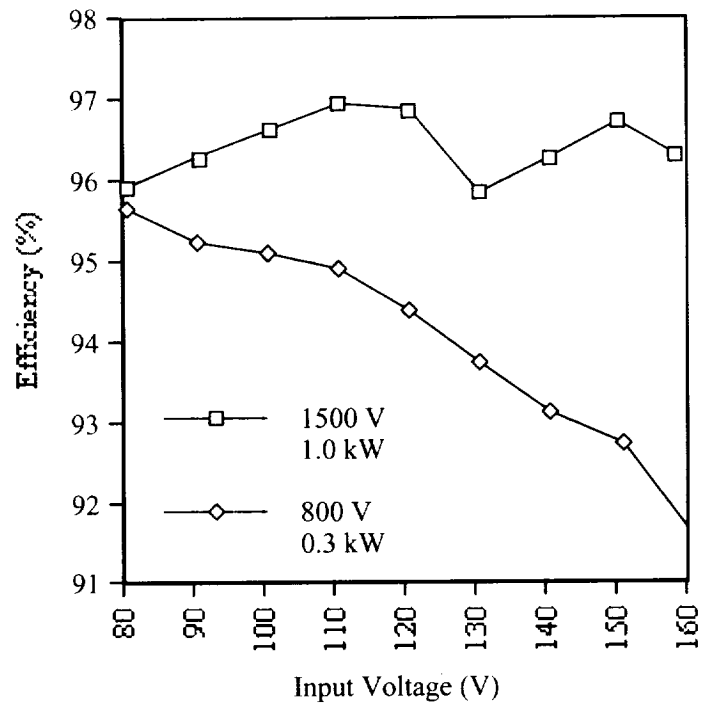


Figure 9. Beam Power Module Efficiency vs. Input Voltage

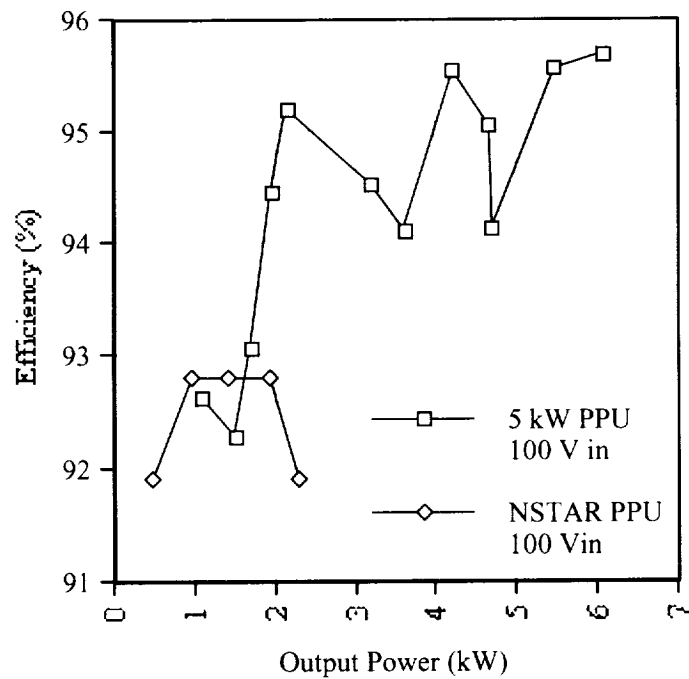


Figure 10. Estimated 5 kW PPU Efficiency vs. Output Power

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